Ganymede vs. Europa: Comparisons of Sulci at the Regional Scale. R. T. Pappalardo [1], J. W. Head[1], R. Greeley[2], R. Sullivan[2], M. H. Carr[3], B. R. Tufts[4], and The Galileo SSI Team, [1]Brown Univ. (Dept. Geol. Sci., Box 1846, Providence, RI 02912; pappalardo@brown.edu), [2]Arizona State Univ. (Geology Dept., Box 871404, Tempe, AZ), [3]U.S.G.S. (Menlo Park, CA), [4]LPL (Univ. Arizona, Tucson, AZ).

A portion of Europa's "wedges" province, near the satellite's anti-jovian point, was imaged by the Galileo SSI instrument on orbit C3. Dark wedges in the region show broad morphological similarities to grooved terrain on Ganymede as that terrain appears at Voyager resolution. (The C3 Europa resolution of ~420 m/pxl is close to that of the best Voyager Ganymede images, ~550 m/pxl). Here we explore the morphological comparison of lanes of grooved terrain ("sulci") on Ganymede to Europan wedges imaged by Galileo. The morphologies show overall similarities, but important differences imply that processes which shaped ridge and trough terrain on these two satellites were likely very different, probably reflecting differences in thermal properties of the satellites' icy lithospheres.

Ganymede grooved terrain vs. Europa wedges
Ganymede. Voyager images show that grooved terrain on Ganymede consist of sets of curvilinear, subparallel ridges and troughs, which occur in structural cells a few tens to ~100 km wide [1]. Ridges and grooves commonly trend subparallel to the boundaries of individual structural cells; relationships are more intricate in regions within broader swaths of cross-cutting cells, termed complex grooved terrain [2]. Spacing of ridges and troughs within a single groove set tends to be regular; Voyager data showed a regular mean trough spacing of about 8 km [3], but high resolution Galileo images reveal finer scale structures spaced ~1 km apart [4]. Based on Voyager images, crosscutting and termination relationships among grooves identifies them as tectonic, and the continuum of forms from single troughs to ridge-and-trough sets suggests a genetic relationship and an extensional-tectonic origin; similarly, an extensional origin is implied by relatively deep troughs that commonly define the margins of sets [1,5,6]. Such an origin implies that troughs are either normal fault blocks (tilt blocks and/or graben), or crevasse-like tensional fractures [7-9]. Some individual Ganymede sulci that cut dark terrain taper to a point (e.g. Anshar Sulcus), suggesting extensional opening about a rotation pole. Some groove sets within more complexly deformed sulci show a sigmoidal shape overall, suggesting a component of horizontal shear [10,11]. Some display prominent medial ridges or troughs and rough bilateral symmetry; this led to consideration of an origin through spreading [10], but the lack of split pre-existing features or subduction-like margins means there is no direct evidence for this model on Ganymede [7,12]. Galileo high resolution imaging confirms an extensional tectonic origin through normal faulting, and demonstrates the importance of a component of horizontal shear in the formation of grooved terrain [4]. Troughs do not show the morphologies predicted for viscously relaxed tension fractures [9].

Europa. Voyager studies of the reconstruction of wedge-shaped and gray bands [13, 14] support the hypothesis that features such as the wedges observed by Galileo formed through separation of lithospheric plates by an amount essentially equal to their widths, with associated volcanic "infilling" by dark material. This hypothesis is supported by Galileo images of Europa's wedges region on orbit G1 [15].

Galileo C3 imaging demonstrates that Europa's wedges are comprised of subparallel ridges and grooves that in turn generally trend subparallel to the boundaries of the set in which they occur [16]. Like isolated Ganymede sulci, the most prominent C3 Europa wedge tapers to a point, implying opening about a rotation pole [cf. 13]. This wedge shows a prominent medial ridge (as do some Ganymede sulci, e.g. portions of Mashu Sulcus) and bounding troughs (common to Ganymede sulci, e.g. Tiamat Sulcus). The other prominent

C3 Europa wedge shows a sigmoidal-shaped region of ridges and troughs, suggesting dextral shear during deformation, consistent with reconstruction of these features [17]. However, little can be said of the morphologies of the constituent ridges and troughs of Europan wedges, as they are near the limit of resolution of Galileo C3 imaging. In this region of Europa's bright plains, ridges and grooves appear to cross-cut one another in stratigraphically superposed sets, grossly analogous to Ganymede's complex grooved terrain.

Ganymede vs. Europa. Despite these broad morphological similarities, there are fundamental differences between the regional-scale geology of these two satellites. First, at this scale Europa shows many isolated ridges and relatively few isolated troughs. In contrast to Ganymede's ubiquitous furrows and grooves, the ridge appears to be the primary morphological component of Europa's surface. Second, boundaries of the Europa wedges appear to be composed of arcuate segments, as are many of Europa's structures. Although Ganymede's sulci can change trend abruptly (likely due to control by pre-existing structure such as furrows [e.g. 2]), they typically do not follow arcuate segments. Third, and most important, examination of Europa's wedges show that they can be reconstructed (i.e. closed) with few gaps or overlaps [16,17]. This implies that they have opened by an amount equal to their widths, indicating complete separation and spreading of the Europan lithosphere along a sharp and distinct boundary. Attempts at reconstruction of Ganymede's sulci from Voyager images has been generally unsuccessful [6,18].

Tectonic Resurfacing vs. Spreading
The first-order similarity of Ganymede sulci to Europa's wedges suggests that two endmember hypotheses should be considered for the origin of sulci and their constituent ridges and troughs on these satellites: 1) a rifting or "tectonic resurfacing" model [4,19], in which normal faulting is the principal process that has shaped the ridge and trough terrain, perhaps combined with icy volcanism; and 2) a "spreading" model, involving complete separation of the lithosphere with new material forming in between, in which linear volcanic constructs and extensional tectonic structures likely form the constituent ridge and trough features [7].

In the rifting or "tectonic resurfacing" model, proposed for the Uruk Sulcus region of Ganymede [4,19], ridge and trough terrain is created through tilt-block style faulting and thinning of pre-existing lithosphere. Preliminary estimates for extension across some Uruk Sulcus groove lanes on Ganymede are large [20], but this rifting model does not propose complete lithospheric separation to form sulci. Complete separation of the lithosphere to create Europa's wedges implies that the constituent ridges and troughs may be tectonic and/or magmatic in origin, perhaps reflecting incremental opening of the feature, with new material emplaced through intrusive and extrusive magmatism combined with extension-induced faulting or fracturing. The topographic wavelength of Europa's ridges appears to be comparable to the 840 meter per line pair resolution of C3 imaging, similar to the widths of ridges measured in Galileo images of Uruk Sulcus.

Lithospheric Strength: Ganymede vs. Europa
The differences in sulcus morphology and tectonic style on Ganymede and Europa can be best understood in terms of the different responses of the satellites' lithospheres to regional tensional stress. For Europa, there has been much consideration of high thermal gradients and the possibility of a liquid ocean beneath its icy surface, based in part on the paucity of impact craters and its style of tensional

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deformation [13,21]. To directly compare the brittle lithospheres of the two satellites, Figure 1 presents lithospheric strength envelopes for Ganymede and Europa in tension. It is assumed that impurities (e.g. silicates) are of small enough volume fraction that water ice controls the brittle and creep behavior of the lithosphere [22]. Curves describing the ductile behavior of ice [23] are labeled with plausible thermal gradients, from 5 to 100 K/km. For each satellite, the assumed strain rate is 10^{-15} s^{-1} (3%/Myr) and surface temperature is 100 K. A lithosphere density of 1.0 g/cm^3 is adopted, allowing for minor ice impurities. Kinks in the creep curves represent change in the ductile behavior of ice with temperature. Dots at the lower ends of these ductile curves indicate the melting depth of ice (i.e., the depth to an ocean) for the thermal gradient and surface temperature assumed, potentially applicable to Europa. The lines **a**, **b** and **c** are different assumptions for the brittle strength of the lithosphere as a function of depth. Lines **a** and **b** represent laboratory data on the frictional strength of ice (the "Byerlee's Law" for ice [24]) for Europa's gravity of 1.31 m/s^2 (solid lines) and for Ganymede's gravity of 1.43 m/s^2 (dashed lines). Line **a** is the best fit to the laboratory data, while line **b** passes through zero and thus assumes that the lithosphere has negligible cohesion [24]. As previously inferred for Europa [25], line **c** describes an ice lithosphere controlled by the strength of polycrystalline (i.e. annealed) ice, and a Griffith failure criterion is adopted for this curve, with an assumed ice tensile strength of 2.5 MPa. The intersection of the ductile curves with the lines **a** and **b** gives appropriate bounds on the strength in tension of a frictionally controlled lithosphere, and on the thickness of the brittle ice lithosphere if it is pervasively fractured and thus frictionally controlled (i.e. the depth to the brittle/ductile transition). The intersection with line **c** provides this information for a polycrystalline ice lithosphere. A fractured lithosphere is considered a valid assumption for much of Ganymede's lithosphere, and a cohesive polycrystalline ice lithosphere may be appropriate to Europa's warmer (potentially largely annealed) lithosphere. These strength envelopes can be compared to those of [25,26], who employ a similar approach but use an oler ice flow law. The presence of ~800 m wide graben on Europa concentric to a circular structure (palimpsest?) imaged on orbit E4 [27] has important implications for the nature and strength of the Europan lithosphere. They imply that at least the near surface must be comprised of fractured material, rather than crystalline (annealed) ice, as the confining stress necessary to permit normal faulting to form a graben cannot be attained at a shallow depth (<~6 km for Europa) in a crystalline ice lithosphere [25]. Shallow-depth graben may indicate that the upper lithosphere of Europa may not be annealed, such that at shallow depth its brittle strength may be bounded by curves **a** and **b**, while following curve **c** at greater depth.

A higher thermal gradient on Europa could explain the fundamental differences in its geology from Ganymede, as less tensional stress would be needed to rupture completely through a significantly warmer, thinner Europan lithosphere despite the greater strength of an annealed lithosphere relative to one that is fractured. Lithosphere-penetrating fractures in a thin (<~6km thick) warm Europan lithosphere should be in the style of near-vertical fractures [25]. On the other hand, deformation in a colder, pervasively fractured Ganymede lithosphere will be in the style of normal faults. Differences in the degree and expressions of deformation on Ganymede and Europa may also reflect differences in the relative degree of tidal stress experienced by the satellites. As the arcuate nature of many Europan features is not yet understood, it is uncertain whether differences in lithospheric properties (e.g., the extent of annealing) might create this contrast between Europa and Ganymede. The prevalence of isolated ridges on Europa, if they are of magmatic origin (i.e.

constructional or intrusive [7]), might also reflect a high thermal gradient and a thin, weak lithosphere.

If a "plate tectonic" analogy holds true for Europa, it is worthwhile to reconsider whether lithospheric separation could have played a role in the formation of grooved terrain on Ganymede in regions of greatest lithospheric thinning and highest local heat flow. This may also be relevant to other icy satellites that show lanes of parallel ridges and grooves, specifically, Miranda and Enceladus. For Ganymede, the fact that split craters are not seen in dark terrain across sulci [6] does not rule out the possibility of local lithospheric separation, for example along the central portions of some sulci, with tectonic resurfacing and/or cryovolcanism destroying pre-existing features along the rifted margins. To date, Galileo images reveal no direct evidence for lithospheric separation on Ganymede; additional high resolution imaging (especially of Tiamat, Anshar, and Erech Sulci on orbit G8) will address the feasibility of partial lithospheric separation across Ganymede sulci.

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